# Magnetic Circular Dichroism Study of Ni/Pt Multilayer Films

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## INTRODUCTION

Extensive experimental[1] and theoretical[2] studies have investigated how the magnetic moments are modified in size and/or orientation in ultrathin films. As for Ni films, a fundamental issue of the existence of magnetically dead layers still remains open because the experimental results and theoretical predictions have given some controversy[1,2]. Room-temperature perpendicular magnetic anisotropy (PMA) was also reported in Ni/Pt multilayers and its phenomenological origin was linked to magnetoelastic anisotropy[3]. However, the intrinsic microscopic origin of PMA and the existence of the magnetically dead layers of Ni remain open to question. In this work, we provide clear experimental evidence for the room-temperature magnetically dead layers of Ni and the microscopic origin of PMA in Ni/Pt multilayers, by measuring angle-dependent magnetic circular dichroism (MCD) and Ni-specific hysteresis loops through the Ni $L_3$ MCD contrast that provides a submonolayer sensitivity. The spin and orbital magnetic moments, and their anisotropy compensated for the nonmagnetic Ni layers were determined from the angle-dependent MCD spectra without saturation or thickness effects usually incorporated in typical MCD measurements.

## EXPERIMENTS

A series of Ni/Pt multilayer samples were prepared at room temperature on 1600-Å-thick $SiN_x$ membrane substrates by sequential dc magnetron sputtering of Ni and Pt under a base pressure of $8\times10^{-7}$ mTorr and at an Ar sputtering pressure of 7 mTorr. (111)-oriented polycrystalline and multilayer structures were confirmed by x-ray diffraction study. The multilayer structure was desired to be $[x$-Å-Ni/4.5-Å-Pt$]_n$, where the repeating number $n$ = 2, 4, or 7, and the Ni sublayer thickness $x$ = 2 - 31 Å. All the samples were capped with 10-Å-thick Pt to protect from oxidation. Total thickness of all the films was intended to be less than 100 Å to exclude the thickness effect on MCD spectra in transmission measurement. MCD measurements were carried out using an out-of-plane elliptically polarized beam from bending magnet at the beamline 6.3.2. The degree of circular polarization was determined, $P_c$=0.77 directly measured from a polarimetry. MCD spectra were taken at room temperature by reversing the magnetic field direction and by monitoring transmitted intensities of +/- helicity through samples. The +/- helicity represents the sample magnetization parallel and antiparallel to a fixed photon spin in our case. Angle-dependent measurements of the MCD were made at incident angles $\theta$=90° and 35° from the film plane. The direction of a magnetic field of +/-2.8 kOe is parallel to the incident x-rays at both angles. Ni-specific hysteresis loops were measured by applying the magnetic field up to +/-2.8 kOe while measuring the MCD contrast at the Ni $L_3$ edge at both directions.

## RESULTS

Fig. 1 (a) shows the transmitted intensity at $\theta$=90° for $x$ =30.5 Å as an example. Difference in transmission spectra between +/- helicity is strongly enhanced at the $L_2$ and $L_3$ edges. A cross-check of $x$ is necessary because the precise $x$ is crucial in clarifying the room-temperature magnetic dead layers observed in this study. Thus, we used post edge jumps to determine the precise $x$ based on the fact that the edge jumps are exactly proportional to the total thickness of Ni sublayers $t_{Ni} = nx$ and independent of the magnitude of resonant absorption "white lines" at the $L_{2,3}$ edges. As seen in Fig. 1(b), by subtracting linear background over the pre-edge region, we can measure edge jumps over the post-edge well above the $L_2$ edge. Fig. 2 shows Ni edge jumps versus $t_{Ni}$, where the edge jumps of the other samples are normalized by that of $x$ =30.5 Å. The $x$ estimated only from edge jumps are in good agreement with the $x$ determined in the preparation of the multilayer films.

With knowledge of the measured $x$, the $L_3$ MCD contrast was used to measure Ni specific magnetic hysteresis loops, while $h\nu$ is tuned at the $L_3$ edge, where a maximum of the MCD contrast occurs. Fig. 3 shows the hysteresis loops measured at $\theta$=90° and 35° for all multilayer samples, where the $L_3$ MCD contrasts were normalized by $t_{Ni}$ of each sample. Decreasing magnetic contrast with decreasing $x$ in Ni/Pt multilayers are evident, and the MCD $L_3$ peaks are suppressed to zero below about $x$ = 7 Å, indicating the entire suppression of magnetic moments at room temperature. We stress that the Ni absorption spectra are clearly measured even for $x$ = 2.2 Å, but no MCD contrast, as seen in Fig. 4. The MCD $L_3$ peaks in magnitude are consistent with the relative saturation magnetization in the observed hysteresis loops. From the hysteresis curves at both angles, the easy axis of magnetization was determined to be perpendicular to the film plane for $x$ = 30.5 Å, indicating PMA, while the others show unclear magnetic anisotropy, but show slight increases in magnetization with magnetic field measured at $\theta$=35°.

Spin and orbital sum rules[4] provide quantitative values of the orbital $M_L$ and spin $M_S$ moments that are related to the integrated intensities of MCD and average XAS spectra of +/- helicity over the $L_{2,3}$ edges. To determine the $M_s$ and $M_L$, the number of holes $n_h$=1.45 for Ni is chosen that is calculated in theory.

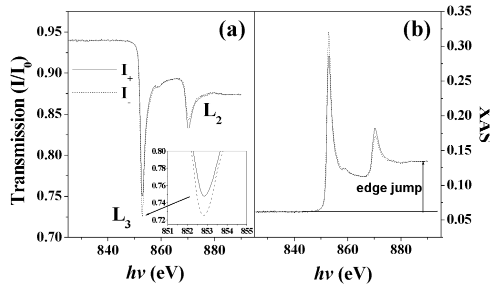


Fig. 1. Transmission spectra $I_{+(-)}/I_0$ corrected for $SiN_x$ membrane and sample-out transmissions for $x$=30.5 Ă at $\theta$=90°, and (b) the corresponding absorption spectra.

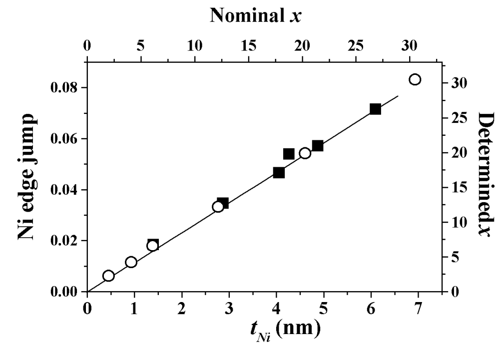


Fig. 2. Post edge jumps (squares) for Ni versus the total thickness of Ni sublayers $t_{Ni}$=$nx$ and determined values of $x$ versus nominal $x$.

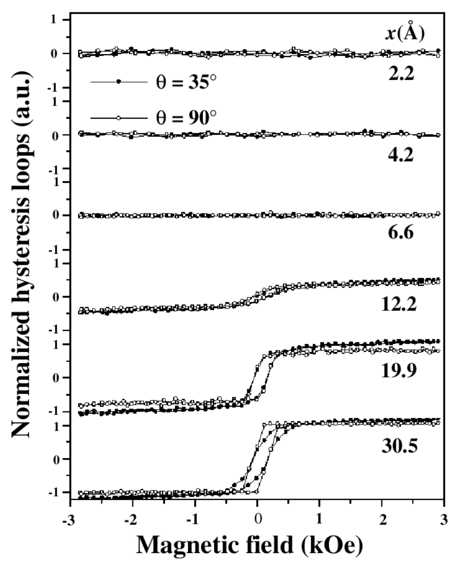


Fig. 3. Magnetic hysteresis loops measured at $\theta$=90° (open circles) and 35° (closed circles) using MCD contrast at the Ni $L_3$ edge. Saturation magnetizations are normalized by the total thickness of Ni sublayers.

Table I. $M_L$, $M_{Se}$ per $\mu_B$ ,and its ratio determined from MCD spectra for both directions.

| $x$ (Å) | $M_L$ | $M_{Se}$ $\theta = 90°$ | $M_L/M_{Se}$ | $M_L$ | $M_{Se}$ $\theta = 35°$ | $M_L/M_{Se}$ | $M_L$(in-plane) | 7 $M_T$ (perpendicular) | $M_S$ | $\Delta M_L$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 30.5 | 0.09 | 0.41 | 0.22 | 0.03 | 0.44 | 0.07 | 0.001 | 0.023 | 0.44 | 0.09 |
| 19.9 | 0.11 | 0.30 | 0.37 | 0.09 | 0.30 | 0.31 | 0.08 | -0.004 | 0.30 | 0.03 |

Based on the analysis described in Chen *et al.*[5] as shown in Fig. 5, the values of $M_L$ and $M_{Se}$, and its ratio at $\theta$=90° and 35° for $x$ = 19.9 and 30.5 Å are determined in Table I. Values for samples with smaller $x$ could not be determined because of their small MCD signals. Directional anisotropy in $M_L$ is determined from angle-dependent MCD measurements[6]. The resulting values are shown in Table I.

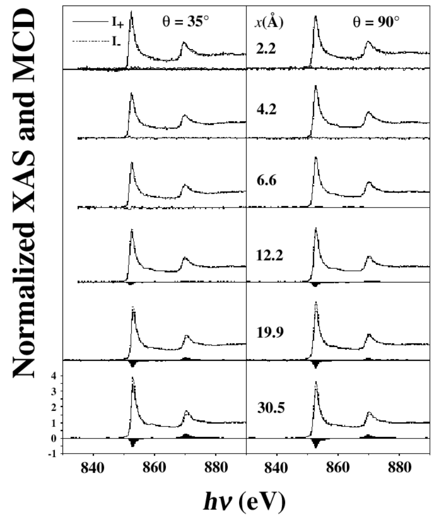


Fig.4. +/- helicity XAS normalized to a per atom and MCD spectra corrected for $P_c$=0.77, measured at $\theta$=35° and 90°.

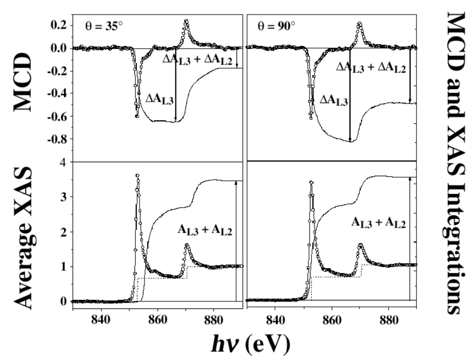


Fig. 5. The MCD and average XAS spectra, and their integration over $h\nu$ after subtracting a two-step function from the average XAS.

## CONCLUSIONS

We have measured angle-dependent MCD spectra across the Ni $L_{2,3}$ edges and hysteresis loops through the strong $L_3$ MCD contrast for multilayer films. Results provide unambiguous evidence for room-temperature nonmagnetic layers of Ni whose thickness is estimated to be $\delta$=5.7 Å from measured $M_S$ versus $x$. The $\delta$ should be considered to determine the values of $M_S$ and $M_L$ of Ni ferromagnetic layers. Large $M_L$ compensated for $\delta$ is estimated to be 0.26 $\mu_B$ for $x$=19.9 Å. In addition, strong anisotropy in $M_L$ results in perpendicular magnetic anisotropy in Ni/Pt multilayer system.

## REFERENCES

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